Chapter 1

Introduction

In this chapter, the general problems of drag reduction are introduced. Some approaches to reduce the drag for attached flows are described in Section 1.2. Examples of reducing pressure drag in mildly separated flows can be found in Section 1.3. The emphasis of introduction in Section 1.4 is placed on the approaches for controlling massively separated flows that occur mainly on the bluff bodies. The last section describes in detail the objective and motivation of this work.

1.1 Problem of Drag Reduction

A body that moves through a fluid experiences a drag force. The force is usually divided into two parts: the friction drag and the pressure drag. The friction drag comes from the friction between the fluid and the body surface over which it is flowing. The friction drag is important for attached flows. It is associated with the development of boundary layers. This kind of drag scales with Reynolds number and is related to the surface area exposed to the flow. The pressure drag comes from the eddying of a wake and is usually less sensitive to the Reynolds number than the friction drag. It is important for separated flows. The pressure drag is related to the cross-sectional area of the body. For a streamlined body, the drag is dominated by the friction drag, whereas for a bluff body, the drag is dominated by the pressure loss.

It is important to discuss the drag sources because the drag is closely related to the flow loss, which is a measure to the flow efficiency. The drag may cause severe problems in the application of fluid machinery or in the natural environment. For example, the transition from laminar to turbulent increases skin friction, although the turbulent flow has more resistance to separation. The separation from surrounding rigid body produces extra pressure drag. Moreover, vibrations and noise can be stimulated. These unsatisfying flow phenomena may deteriorate the operation of fluid machinery, cause the material fatigue and limit the lifetime of the equipments.

The desire to minimize the flow losses in order to improve the performances of fluid machinery and lift devices is providing a driver for increased research activities in this field. It is natural that different methods should be used to manipulate different kind of flows. In the context, the methods for controlling the frictional drag and the pressure drag are introduced, respectively.

1.2 Friction Drag Reduction

Since the friction drag comes from friction between the fluid and body surfaces and is defined by $\tau_w = \mu \frac{\partial u}{\partial y}$ in Newtonian fluid, one solution to reduce the drag is to try to achieve a significant laminar flow extent. The polishing of the surface is a good solution to this problem.

Once the turbulent boundary layer has been developed, the friction drag can be reduced through using the turbulent boundary layer manipulators. Given in Figure 1.1 is a sketch of the riblets. Typical riblets are about 0.02~0.2mm high. The spanwise distance *s* is usually of the same order as the riblet height h. Extensive experimental study of riblets for turbulent drag reduction was carried out by Walsh in the late 1970's at the NASA Langley Research Centre.[48] For triangular riblets, skin friction drag can be reduced by up to 8%. It is generally considered that the riblets can suppress the streamwise vortices, weaken the momentum and energy exchange near the wall and, hence, reduce the friction drag. There is still much debate about the exact mechanism. However, all hypotheses are based on the control of the near-wall turbulent coherent structures.

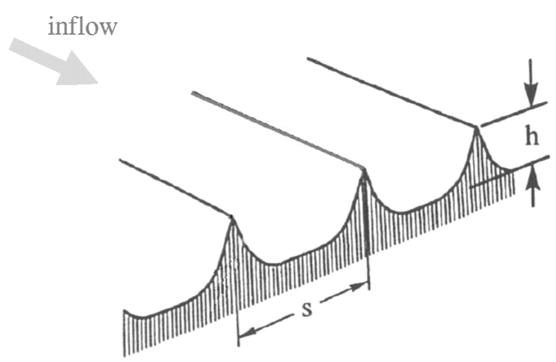
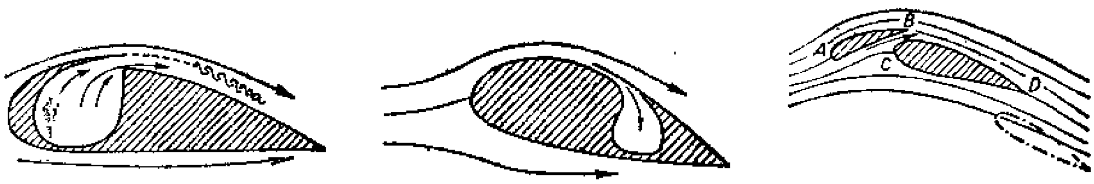


Fig. 1.1. Sketch of riblets arrangement

1.3 Pressure Drag Reduction

The separated flows may bring about more drag than unseparated ones. An earlier transition may be expected because the turbulent boundary layer has more resistance to the separation than the laminar one. The transition control can be realized by, for example, trip wire or surface roughness. Besides, for airfoil flows, the tangential blowing that is sketched in Figure 1.2(a) or suction in Figure 1.2(b) can also work because they accelerate the stagnated flows near the wall and give the flow more resistance to separation. Other examples are leading- or trailing-edge extensions in Figure 1.2(c). With leading-edge flap, the main-flow energy can be used to provide additional energy to the stagnated flow in the boundary layer of the main airfoil. The higher pressure from the pressure side of the flap can be diverted to the stagnated region on the suction side through a narrow passageway. The boundary layer on the leading-edge flap mixes into the main flow before it separates. New boundary layer would be formed on the main airfoil. Under certain condition, this boundary layer can be retained unseparated along the whole surface. The trailing-edge flap has similar mechanism as the leading-edge one.



(a) (b) (c)

Fig. 1.2. Boundary layer control using (a) internal blowing, (b) suction and (c) leading- and trailing-edge extensions; from Schlichting[37]

Another example to control the separation is the vortex generators whose general application on the wing is sketched in Figure 1.3. They are usually used to delay flow separation occurring on various parts of an aircraft. Conventional vortex generators are typically vanes arranged in co- or counter-rotating arrays having a height at least equal to that of the local boundary layer. They generate vortices on their top region. The vortices transport fluid elements of high velocity into the near wall region, which gives the flow more resistance to separation. Although vortex generator technology has advanced little over the last decades, there has recently been a renewed interest shown for this technology because the experiments are beginning to show that with good design and careful consideration, vortex generators can be as effective as much larger devices. Some review of the turbulent flow control can be found in Warsop.[51]

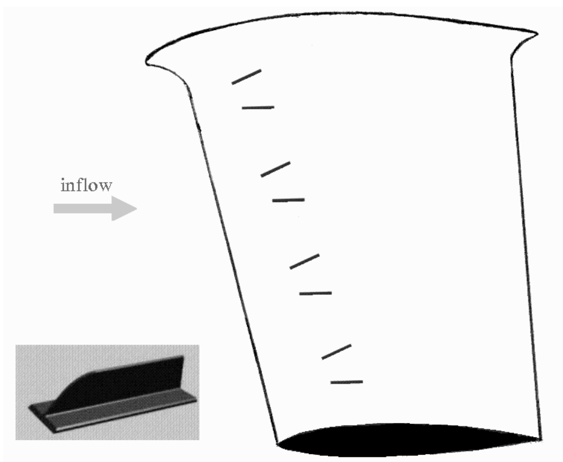


Fig. 1.3. Sketch of structure and arrangement of vortex generators on wing

1.4 Massive Separation Control

It can be found that the above-mentioned control approaches concern mainly the influence on the boundary layer. They are applicable only when the boundary layers are well recognizable. That is, the flow is either fully attached, or with narrow separation region. For these cases, the drag reduction can be achieved by reorganizing the boundary layers. There is, however, another type of flow that makes the concepts of boundary-layer control ineffective. They are so-called “massively separated flows”.

Massive separation occurs mainly on the bluff bodies, like circular cylinders or airfoils at high angles of attack. This kind of separation involves large open region with reverse flow that is usually named as "dead-water region". The dimension of the separation region is comparable to the dimension of the airfoil or structure. The separation control on such configurations remains to be highly interesting because the massive separation may cause certain severe problems. For example, the separation may deteriorate the operation of fluid machinery. On aircraft, it may destroy the aerodynamic characters as increase the drag and reduce the lift dramatically. Certain accompanied flow instabilities may occur that lead to serious safety problems.

This kind of separation is extremely difficult to manipulate because there are enormous flow masses in the region and the vortices are disorderly arranged. These features make the conventional tools as steady blowing or suction useless because the loss overweighs the gain. Therefore, other strategies must be sought to reduce the flow losses in such flows. In fact, some experiments have shown that effective approaches do exist. However, they remain to be active fields of investigation as the exact mechanisms are far from clear. Summarized below are some ideas and experiments proven to be effective on suppressing the massive separation.

A direct way to control the massive separation is to prevent the figuration of the boundary layer, as it is one of the necessary conditions of the separation. A typical example is the moving wall effect on a rotating circular cylinder, in which the prerequisite of the formation of boundary layer is revised through the rotation of the wall. This kind of active control was done by Prandtl for the first time. It is observed from the experiment that the

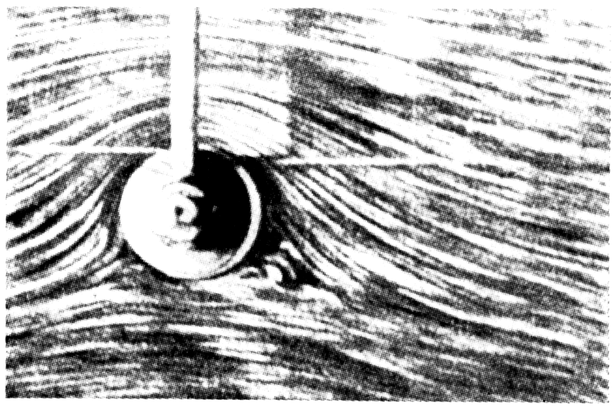


Fig.1.4. Flow around a rotating cylinder; from Schlichting[37]

flow attaches to the surface on the side that has the same moving direction with the outer flow. This is because relative motion between the wall and the outer flow is reduced. Extra momentum can also be provided from the moving wall to the near-wall flow. Therefore the development of the boundary layer is suppressed. On the other side of the circular cylinder, the separation occurs. The whole flow field is very similar to a potential case and is often called "Magnus Effect". A comprehensive experimental investigation on the airfoil with moving surface was carried out by Favre in the 1930' years, in which part of the upper surface of an aircraft wing was substituted by a moving belt driven by two hoops.[11] The turn-round part of the belt was hidden under the surface and had no contact with the outer flow. The installation was proved very effective in avoiding flow separation. At the angle of attack of 55 degrees, the result of Cl_{max}=3.5 was obtained. Unfortunately, except the circular cylinder, the extensive application of such device in industry is limited because it would be quite complex to realize the oriented motion of the wall to the flow.

It has been accepted recently that the flow has certain receptivity to small disturbances, e.g. acoustic excitations. Many researchers showed the validity of the sound wave on suppressing the separation on airfoils. Peterka and Richardson in 1969 and Blevins in 1985 have found that external acoustic excitation can change the flow structure of a circular cylinder if the exciting frequency lies in the vicinity of the frequency of the shear-layer instability or the vortex-shedding frequency.[31][3] Applications on separated airfoil flow have been realized by Ahuja et al. in 1983 and Zaman et al. in 1987, etc.[1][54] They have also found that the sound wave can reattach the stalled airfoil flow and therefore, improve the stall performance.

The research group of Hsiao has found that the internal acoustic excitation is much more effective than the external one.[15] They have investigated the effect of acoustic excitation on an $NACA63_3$-018 airfoil at stall and low post-stall angles of attack under different Reynolds numbers. In the experiment, the sound was generated and led to a slot located on the airfoil surface. They showed that between 18 and 24 degrees, the separated flow can reattach to the airfoil surface under certain exciting frequencies and the leading-edge flow separation is delayed. Therefore, the stall and aerodynamic characters can be improved. Flow visualizations for uncontrolled and controlled cases at angle of attack of 20 degrees are depicted in Figure 1.6. The picture in Figure 1.6(b) shows the resulting flow under the excitation of the sound wave at 30Hz. Partial reattachment can be well

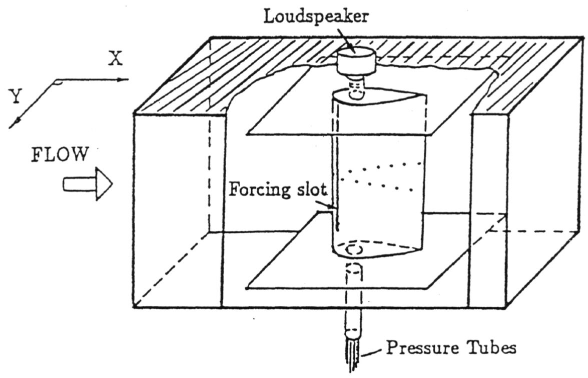
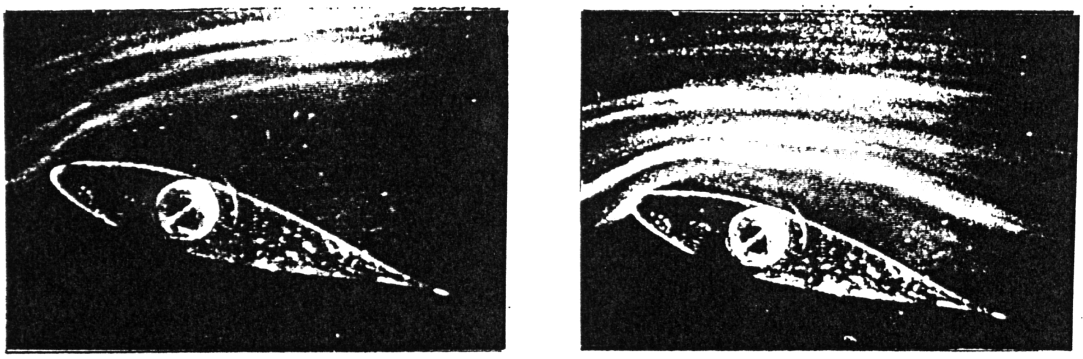


Fig. 1.5. Experimental setup of acoustic excitation; from Shyu[40]

observed. They have also found that the most effective exciting position is near the separation location with the frequencies in the range of shear-layer instability frequency. If the frequencies of the acoustic disturbances coincide with the natural frequencies of the flow instabilities, the interaction is usually of highest effectivity. In their research, effective frequency can extend to over 1000Hz. They have proposed that the governing parameter is not the sound pressure intensity but the velocity fluctuation generated by the loudspeaker. However, the argument is doubtful because there is theoretically little resonance possibility between the sound and the characteristic wave in the shear layer. The sound speed is much higher than the speed of the characteristic wave in shear layer. The energy exchange between both waves should be very limited. The exact acting mechanism of this kind of excitation is not yet fully understood.



(a) (b)

Fig. 1.6. Flow visualizations of (a) uncontrolled and (b) controlled by 30Hz NACA63_3-018 airfoil at angle of attack of 20 degrees, from Shyu[40]

Another effective approach on controlling the massive separation is the unsteady blowing containing an oscillatory blowing and a small amount of steady blowing. The oscillatory part contributes no net mass. The blown fluid is tangential to the airfoil surface. This kind of blowing is promising because it requires less power input. A 25%-chord flapped NACA0015 airfoil was investigated by Seifert et al.[38]

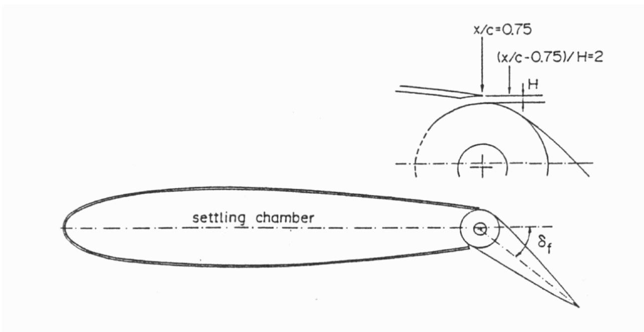
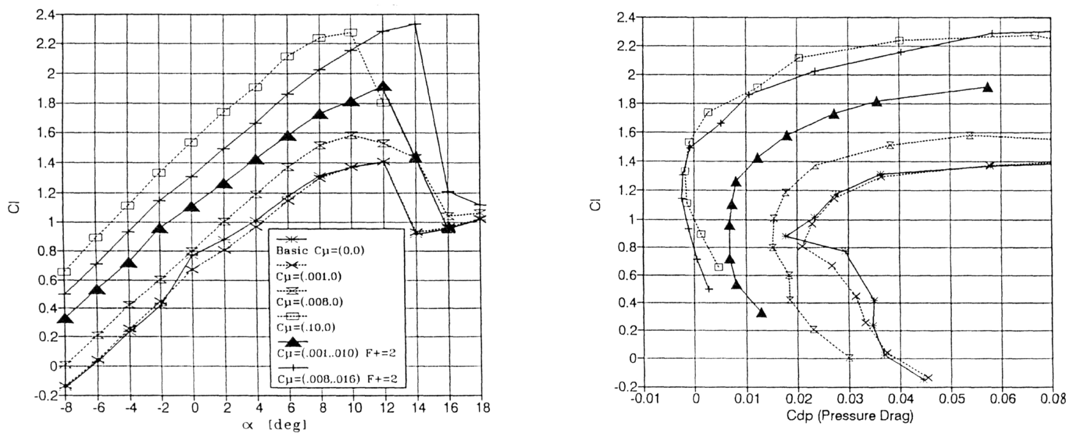


Fig. 1.7. Experimental setup of tangential blowing; from Seifert et al [38]

With proper combination, the stall angle of attack can be delayed. The aerodynamic performance can be improved through lift increase and drag reduction. The amount of blowing momentum is generally an order of magnitude smaller than that required by steady blowing achieving comparable gains. The results of the lift coefficient and polar are shown in Figure 1.8.



(a) (b)

Fig. 1.8. (a) Lift and (b) polar curves obtained by tangential blowing; from Seifert et al [38]

Further experiments by Seifert et al on the same airfoil structure are carried out with blowing at the leading edge where the surface was locally roughened to obtain a turbulent boundary layer.[39] The introduction of periodical oscillations at the leading edge enables the boundary layer to resist large adverse pressure gradients without separation. The result of lift coefficient is presented in Figure 1.9. It is clear that the leading edge blowing can achieve better results than the flap blowing. The stall angle of attack can be delayed by 8 degrees. At least two eddies are present over the upper surface of the airfoil at any instant of time and their size increased in the direction of streaming. For an effective control, the amplitude of the imposed oscillations should peak in the vicinity of the natural

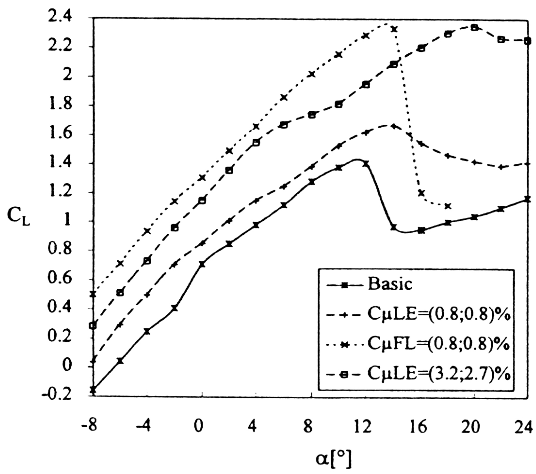


Fig. 1.9. Lift coefficient curve by different combination of tangential surface blowing; from Seifert et al [39]

separation location. The most effective frequency seems to be one, in which the streamwise length was comparable to the average wavelength of the imposed periodic disturbances. The length of the surface downstream of the natural separation location is the most significant length scale in this control problem and not the thickness of the upstream boundary layer.

It is worth mentioning that the development of new manufacturing technologies, such as Microfabricated Electro-Mechanical Systems (MEMS) (see e.g. McMichael[28]), and solid state actuator technologies, such as piezoelectric materials and shaped-memory alloys, has also led to the possibility for realizing flow control at both macro and micro scales. But these are now only in the initial design stage and there remains a long way to the practical applications. Therefore the author would like not to discuss them in this work.

The above classification of the flow control is, of course, not unique. For example, the control approaches can also be classified as active or passive according to their energy requirement. A control method is active if extra energy is input for sensors or actuators. The method can be passive if there is no extra energy given to the flow. Suction, blowing, moving wall, acoustic excitation, etc. are typical active, while vortex generators, leading- or trailing-edge extensions, etc. are among the popular passive approaches. Important requirements on active control are, firstly, the input energy should not have negative influence on the flow and secondly, the necessary energy supply should be less than the gains. Other classifications of control method, for example, open-loop or closed-loop control, are possible. But they will not be discussed in this work.

1.5 Motive and Objective

It can be concluded from above description that because the separation at high angles of attack of an airfoil has large dead-water region, the attempts to remove the whole separated flow using single suction or blowing are impractical. However, the flow shows certain receptivity to small unsteady disturbances like acoustic excitation or unsteady jet. There must be the possibilities that we should adopt to control the separation at the stall or post-stall angle of attack.

The dissertation aims at the improvement of statistical turbulence models on predicting separated airfoil flows and the investigation on the synthetic jets on suppressing massively separated flows and their possible applications in fluid machinery. The jet is synthesized at a fluid boundary perpendicularly opened to the fluid from a small orifice through which the fluid is alternately ingested and expelled. The jet contributes no net mass. But it does impart a net momentum to the fluid.

In Chapter 2, one can find a brief introduction to the mathematical and numerical foundations. Because of the inability of existing turbulence models on predicting massively separated airfoil flows, a modified model is proposed and validated for two characteristic angles of attack of an NACA63_3-018 airfoil. Detailed information about the turbulence models can be found in Chapter 3. The effects of synthetic jets on this NACA63_3-018 airfoil at stall angle of attack are presented in Chapter 4. The jet influence on a one-stage stator-rotor arrangement is discussed in Chapter 5. Finally, a summary of the current work and an outlook of future work are available in Chapter 6.